

ENTROPY, EXTROPY AND THE PHYSICAL DRIVER OF IRREVERSIBILITY

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ABSTRACT

We point out that the fundamental irreversibility of Nature requires the introduction of a suitable measure for the distance from equilibrium. We show that entropy, which is widely held to be such a measure, suffers from the problem that it does not have a physical meaning, since it is introduced on the basis of mathematical arguments. As a consequence, the basic physics beyond irreversibility has remained obscure. We present here a simple but transparent physical approach for solving the problem of irreversibility. This approach shows that extropy, the fundamental thermodynamic variable introduced by Katalin Martinás, is the suitable measure for the distance from equilibrium, since it corresponds to the actual driver of irreversible processes. Since extropy explicitly contains in its definition all the general thermodynamic forces that drive irreversible processes, extropy is the suitable physical measure of irreversibility.

KEY WORDS

extropy, irreversibility, entropy, equilibrium, non-equilibrium, thermodynamics

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INTRODUCTION

Thermodynamics has two fundamental laws, corresponding to the invention of two physical quantities having a central importance in physics: energy and entropy. The first law introduces energy and expresses the law of energy conservation. The Second Law is about the irreversibility of Nature. Although the first concept, energy, can be said to be understood, the second one, entropy, not so. Thermodynamic irreversibility is still somewhat obscure. The main problem with it is that we do not know the physical reason beyond this irreversibility.

ENTROPY IS INTRODUCED MATHEMATICALLY

The measure usually applied for irreversibility is entropy. Somehow entropy came through mathematics as $\int dQ/T$ (dQ the amount of heat transferred in a cyclic reversible process and T is the temperature). But the physical content of entropy remained obscure. Indeed, if it would be physically plausible, entropy would not have come “out of the blue”. Yet, the invention of entropy was unexpected, and, despite centuries of discussions, its physical meaning is still unclear. It is not yet clear why we cannot understand it as we do most other concepts of physics. What we know is that in cyclic processes there are conserving quantities, and the integral of dQ/T for a quasistatic cyclic process is zero.

$$\int \frac{dQ}{T} = 0, \quad (1)$$

It is the mathematically simplest solution of this equation (1) that led to entropy. But actually this is only a specific solution of equation (1), since it has many other solutions as well. Katalin Martinás was the one who first noticed the importance of exploring which one of these solutions can be really useful for our practical purposes [1-6]. She considered the general solution of eq. (1). Apparently, most scientists seem to think that thermodynamic irreversibility can be measured only by entropy. But this is not true, and Martinás succeeded to find another useful quantity which is extropy (references given above).

We think that the physical nature of entropy will remain forever unclear, yet we do not have to worry about it if we recognize that entropy is a mathematically introduced quantity [7]. Therefore, we have to replace the mathematical context by a physical one. If we want a measure of irreversibility with a physical meaning, we must introduce it not on a mathematical, but on a physical basis.

A PHYSICAL APPROACH FOR THE PROBLEM OF IRREVERSIBILITY

My proposal here is to find the most general measure of equilibrium which has a definite physical content. To solve this fundamental problem, we must go back to square one, to the problem of irreversibility. Nature is fundamentally irreversible. Everything is in the process of changing, since everything is in non-equilibrium, and it is the driver beyond it that moves systems towards equilibrium. Irreversible process has a dynamic nature. Irreversibility starts from non-equilibrium states. If a system is not in equilibrium, it has a distance from equilibrium, and this distance changes. Although changes of Nature can be regarded frequently as chaotic, especially in thermodynamics, the case with irreversibility is not so. The changes of the distance from equilibrium do not show chaotic or random behaviour. Instead, remarkably, they manifest a definite and consequent unidirectionality. Certainly, a mathematical background cannot clarify the basic physics beyond irreversibility. But there must be a physical reason for this unidirectionality.

What can be the physical mechanism beyond unidirectionality of spontaneous changes of a thermodynamic system in an environment in thermodynamic equilibrium? My proposal is that we can obtain a measure of irreversibility that is capable to have a real physical meaning if we realize that the physical driving mechanism beyond irreversibility is given by Nature in the form of generalized thermodynamic forces, which correspond to the differences in the intensive thermodynamic variables that are independent from the size of the system [8]. Actually, all physical processes are elicited by some kind of forces. In classical mechanics, forces attack in one point. Mechanical forces are vector quantities, they have a direction, and the direction of the force attacks the body in a point. A direction of a vector corresponds to one dimension, the dimension of a line. In thermodynamics, we have general thermodynamic forces in the form of differences of the intensive variables. Thermodynamic forces do not attack their target at one point, they are not one dimensional. Instead, thermodynamic forces represent more general forces, they are two or three dimensional, they attack in the form of surface or volume forces. All differences of intensive variables are related to such generalized thermodynamic forces. We have many different types of intensive variables. So, we can construct a much needed physical variable for measuring the rate of irreversibility from these general thermodynamic forces, because these are related to differences, and these differences themselves are the drivers of irreversible processes.

This means that if we become able to collect all the kind of forces, all the kinds of differences of thermodynamic intensive variables between the system and its environment, and construct from them with the help of extensives such a kind of terms which we can sum up in a simplest way [9], then this physical variable could be in itself a scalar quantity defining a measure of thermodynamic distance which is suitable to measure irreversibility.

Moreover, if we want to include into our considerations such processes as the mixing of a glass of water by a spoon, we can extend the domain of extropy from thermodynamics into mechanics. Similarly, if we want to include chemical, electromagnetic, gravitational or nuclear processes, extropy as a measure of distance from equilibrium still can serve well. This means that extropy can be regarded as a universal measure of the distance from equilibrium.

In a general form, extropy can be given as:

$$\Pi = U\left(\frac{1}{T_0} - \frac{1}{T}\right) + V\left(\frac{p_0}{T_0} - \frac{p}{T}\right) + N\left(\frac{\mu_0}{T_0} - \frac{\mu}{T}\right) + mg\left(\frac{h_0}{T_0} - \frac{h}{T}\right) + \dots, \quad (2)$$

Here the zero index refers to the equilibrium state (to the environment regarded as being in equilibrium), the absence of index of a parameter refers to the actual state of the system, Π stands for extropy, U for the internal energy, T for the temperature of the system, V for the volume, p for the pressure, N for the particle number, μ for the chemical potential, m for the mass, h for the height of the system. Extropy explicitly contains all the general thermodynamic forces that are the actual drivers of thermodynamic processes. In biology, such a measure can play a fundamental role [10].

THE PROPERTIES OF EXTROPY

Extropy has many useful properties. First of all, with its help we can understand the physical meaning behind irreversibility. Moreover, it is possible to formulate the Second Law of thermodynamics with the help of this parameter. It is very suitable, because it is a scalar quantity. It measures the distance from thermodynamic equilibrium, and so it is not like geometrical distance, just because of irreversibility. Geometrical distance is symmetric between two points, but this thermodynamic distance is not, since the initial and final states

of this thermodynamic distance play a different role in its formula. Actually, it can be expressed as a product of the differences of intensives and their corresponding extensives. When we sum up all the different kinds of these products, we obtain extropy. In the expression of extropy, all these products can be summed up because all these terms have the same dimension, and measuring unit, erg/degree. What we find is an unexpectedly simple, elegant and general thermodynamic variable, of which the physical meaning is unexpectedly simple, and which is able to interpret irreversibility, that is so fundamental, that the Second Law of thermodynamics expresses it. Therefore, this will be a very helpful and very useful quantity, which will have a fundamental significance for thermodynamics. For many practical reasons, it will be even more useful than entropy. Realizing the power of the physical insight beyond extropy, its use will make thermodynamics easier to understand and apply.

It is applicable also in cases when entropy is silent. In all cases when there are couplings between different degrees of freedom and related energy transfer, extropy is the suitable measure of irreversibility. But not only such cases are important. For example, let us have apples in two different boxes. All what we know is that in the first box the entropy is higher than in the second box. In that case, we cannot decide, without knowing more about the apples, which box contains better apples for us. It can be the case that there are more apples in the first box, which have the same quality than the apples of the second box. But another case is also possible. The same amount of apples is in both boxes, but the apples of the first box are rotten, and so, they have higher entropy. On the basis of entropy, we cannot distinguish which is better, but we can distinguish it on the basis of extropy, because the distance from equilibrium is higher in the latter case.

A NEW CLASSIFICATION OF THERMODYNAMIC SYSTEMS

With the help of this new thermodynamic variable, we can classify thermodynamic systems in a new way. One of them is the class of equilibrating systems, which can be called as entropic, since they are “attracted” towards their end states, the equilibrium. There are heliotropic plants “attracted” towards the Sun. Similarly, equilibrating systems are “attracted” (actually, they are driven) towards the equilibrium. And the other class of systems, i.e. non-equilibrating systems, they are not equilibrating because they interact with other systems. Due to this interaction, their distance from equilibrium can increase or decrease, or remain the same, depending on the details of their interactions. Therefore their behaviour cannot be predicted without knowing the important details of their concrete interactions. Without specifying their interactions, we cannot predict whether their distance from equilibrium, extropy, will increase or decrease. Therefore the entropic and the interacting systems are the two fundamental classes of thermodynamic systems instead of the usual classification dividing them into open, closed, and isolated systems.

COMPARISON OF EXTROPY WITH ITS PREDECESSORS

We can compare this new variable with some important predecessors. Let us take first the Brillouin negentropy. It is a famous thermodynamic variable, which may seem as similar to extropy, because it is also a difference, the difference of the entropy of the system in its actual state and in its equilibrium state, in which it is in equilibrium with its environment. But, besides this similarity, there is a fundamental difference in comparison to extropy. Actually, the Brillouin negentropy is defined only to the properties of the system, and so it does not depend on the properties of the environment [11]. This means that the same system in a different environment will have a different Brillouin negentropy. But, of course, the extropy of a system in a different environment will be different. Extropy measures the distance of the system from its actual environment (for the sake of simplicity, it is regarded as being in

equilibrium), therefore, in a different environment this distance will be different. This means that this new variable is even more suitable in describing the actual behaviour of a thermodynamic system than the famous Brillouin negentropy, since the actual thermodynamic behaviour of a system depends sensitively on the properties of the environment, first of all, from the distance from this equilibrium.

We can compare it also with some other important predecessors, like the also famous Schrödinger negentropy. Schrödinger in his well-known book “What is Life?” argues that living systems are not fed upon directly by the chemical energy of the food. Instead, “What an organism feeds upon is negative entropy” [12]. This is a hotly debated statement, but we think that, although it can be criticised since in some respects it does not grasp the physical driving mechanism beyond life, yet it contains an important physical meaning, which can be expressed in a more precise form with the help of extropy. If we do that, it tells that the factor by which living systems are fed is extropy. The difference between Schrödinger’s negentropy S_N and extropy is that Schrödinger’s negentropy S_N involves only entropy-related changes, $S_N = -S_{\text{system}}$. Therefore, S_N does not involve important changes, like changes in the rotational energy (for example, when somebody mixes the water in the glass by a spoon; hurricanes has tremendous amount of rotational energy), in the kinetic energy (when we pull the glass of water on the table), in the chemical, electromagnetic, gravitational, nuclear energy etc. All these can be accounted for by extropy, since all the relevant intensive-differences and their corresponding extensives are involved into it.

For an isolated system, one which does not interact with its environment, the entropy content of the environment does not change during the equilibration of the isolated system; therefore the entropy of the environment can be regarded as constant. In this case, changes in the the extropy and entropy content of the system are equal. This means that in this simple case Schrödinger’s negentropy works well. Yet we can also see that extropy has a significant advantage over Schrödinger’s negative entropy because it is equally well-suited for non-isolated systems. A further advantage of extropy over Schrödinger’s negative entropy is that extropy, in contrast to Schrödinger’s negative entropy, can be calculated directly by eq. (2). We think that the original idea that Schrödinger had in mind corresponds actually to an exact quantity that we introduced here as extropy.

Extropy sums up all the intensive-differences multiplied by their corresponding extensives. In the calculation of entropy, since it is defined relatively to the absolute zero degree, the determination of its value should involve quantum physical processes. Extropy avoids this difficulty, so it is much easier to calculate it. It is very practical, since this is what counts in actual reality. The difference of the system in comparison to its actual environment is what is distinguished by Nature in determining thermodynamic processes. No system governs its behaviour in comparison to the absolute zero degree state, instead of governing it in their actual relations with their actual environments. It would be a completely unphysical phenomenon. The distance from the actual equilibrium is more fundamental than the distance from the absolute zero degree state. It is this distance from the actual equilibrium that counts in physical reality, since it is in direct and physically real connection with the working ability of the system in its actual environment. It is the physical context of the actual environment that sheds full light to the fundamental priority of extropy over entropy, at least in physical aspects which are related to the actual behaviour or working ability of the system.

THE PHYSICAL MEANING OF EXTROPY AND ITS SIGNIFICANCE

In this way, we can realize the fundamental importance of extropy in thermodynamics. It is extropy that is the driving mechanism beyond irreversibility. In actual reality, physical

processes are governed not by mathematically invented abstract quantities, by statistical weight and mathematical probabilities, like entropy [7], but by the general thermodynamic and non-thermodynamic forces. Although entropy can be more convenient than extropy in many realistic contexts, like in case of isolated systems, and also because it is deeply rooted already in our mindset, the future belongs to extropy. Regarding this perspective, we note that there is an unexpected shift in the nature of our physical concepts, when extropy comes into the central stage. In physics, it is usual to consider that all processes are determined by the properties of the systems. In case of extropy, in contrast to the case of entropy, this not so. Extropy has a fundamentally different nature, because it depends on the differences between the system and its actual environment. This is equivalent with the fact that the arising physical behaviour will be not only determined by the properties of the system itself, but also by its actual, physical environment. In this way, the difference will become fundamental, instead of the properties of the physical objects themselves. The fundamental concept of object is replaced with another fundamental concept: difference. The until now most fundamental and simple concept of physics, physical object, has one leg. In contrast, the here considered fundamental quantity, extropy, already has not one leg, like a physical object, but two legs; the object and its actual environment. Difference has two legs, like in the case of an electric discharge, or in quantum nonlocality. Extropy perceives both legs, it is the distance from between the two legs what counts. This is a very unique property of extropy. Now if extropy is fundamental, as we argued here, than this indicates that Nature can act not only directly on physical objects, but in between physical objects. If so, it will present a conceptual shift in the framework of physics. The more so, because, as we indicate here, it can be important not only in thermodynamics, but in other fields of physics as well in biology. The difference can show up before us in its full significance. The fact that differences can be more fundamental than physical properties of the objects themselves will have a profound effect on the conceptual framework of physics. In the quest of mankind exploring the secrets of Nature, extropy can be regarded as an important step ahead.

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ENTROPIJA, EKSTROPIJA I FIZIKALNI POKRETAČ IREVERZIBILNOSTI

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SAŽETAK

U radu se ističe da fundamentalna ireverzibilnost Prirode traži uvođenje prikladne mjere udaljenosti od ravnoteže. Pokazujem da entropija, koju se uobičajeno smatra takvom mjerom, ima nedostatak da nema fizikalnog značenja jer je uvedena na temelju matematičkih argumenata. Kao posljedica, osnovna ireverzibilna fizika je opskurna. Ovdje razmatramo jedinstavan ali transparentan fizikalni pristup za rješavanje problema ireverzibilnosti. Taj pristup pokazuje da je ekstropija, fundamentalna termodinamička varijabla koju je uvela Katalin Martinás, prikladna mjera udaljenosti od ravnoteže jer odgovara starnom pokretaču ireverzibilnih procesa. Budući da ekstropija izravno sadrži u svojoj definiciji sve opće termodinamičke sile koje pokreću ireverzibilne procese, ekstropija je prikladna mjera ireverzibilnosti.

KLJUČNE RIJEČI

ekstropija, ireverzibilnost, entropija, ravnoteža, neravnotežno stanje, termodinamika